CHIN PROJECTION CHANGES IN HYPO- AND HYPERDIVERGENT CLASS II HERBST PATIENTS AND THE RELATION TO TRUE MANDIBULAR ROTATION

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 2016

Major Subject: Oral Biology

ABSTRACT

The purpose of this study was to examine the relation of chin projection changes and true rotation in hypo- and hyperdivergent patients.

The treated group consisted of 45 growing Class II Division I patients (23 boys, 22 girls) treated by a single practitioner with stainless steel crown Herbst appliances, followed by fixed edgewise appliances. The untreated control group consisted of 45 Class II Div I subjects (23 boys, 22 girls) who were matched to the treated sample based on age, sex, and pre-treatment MPA (SN-GoMe). Pre- and post-treatment lateral cephalograms were traced. Cranial base and mandibular superimpositions were performed to evaluate T1-T2 changes and true mandibular rotation. Cephalometric changes between the treated and control groups were compared.

The primary effect of the Herbst in terms of maxillomandibular correction was in the maxilla. The Herbst produced a significant maxillary growth restriction or a "headgear effect." The rotational effects of the Herbst were different in hypo- than hyperdivergent patients. Hyperdivergent patients experienced a deleterious backward true mandibular rotation with Herbst treatment, while hypodivergent Herbst patients and untreated hypo- and hyperdivergent controls had forward true mandibular rotation. The chin did not come forward any more with Herbst treatment than what was expected to occur in untreated Class II individuals.

Hypodivergent patients may benefit from the Herbst "headgear effect" and may be able to overcome the negative rotational effects of the Herbst, but treatment does not

advance the chin position any more than if the patient was untreated. Hyperdivergent patients also experience a slight “headgear effect,” along with deleterious backward rotation and increased facial height, which worsen facial esthetics. Because of this, hyperdivergent patients are poorly suited for Herbst treatment.

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ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Peter Buschang, and my committee members, Dr. Phillip Campbell, Dr. Larry Tadlock, and Dr. Emet Schneiderman for their guidance throughout the course of this research. I would also like to thank Dr. John Valant for making this research possible by allowing me to use his excellent patient records. I would like to thank my classmates and the department faculty and staff for contributing to such an outstanding educational experience. Finally, I would like to thank my fiancé, Shane, for his constant encouragement and support throughout this research project and residency.

NOMENCLATURE

MPA	Mandibular plane angle
OP	Occlusal plane
Pg	Pogonion
AP	Anteroposterior
Div	Division

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CHAPTER I

INTRODUCTION LITERATURE REVIEW

A bilateral Class II malocclusion is a common problem occurring in approximately 14.7% of the U.S population.[1] Many treatment complexities accompany this malocclusion since facial esthetics are often negatively affected in addition to the dental and skeletal elements. A consistent finding in Class II malocclusion is mandibular retrusion and subsequent retrusive chin position.[2,3] It has been established that a Class II malocclusion develops primarily as a result of mandibular retrusion rather than maxillary prognathism, and generally the skeletal Class II growth pattern is not self-correcting.[2-7] Mandibular growth is significantly different in Class II subjects in comparison to subjects with normal Class I occlusions.[2,7-9] Thus, to correct a skeletal Class II Division I malocclusion, normal anteroposterior maxillary growth must be maintained and greater than normal anteroposterior mandibular growth is required.[3] To correct the facial convexity in Class II individuals, the chin position must also be addressed with orthodontic treatment approaches in order to obtain a significant improvement in facial esthetics. Although not all of the factors involved in facial esthetics are known, a preference for a straighter profile over retrusive chin positions is apparent and well documented in the literature.[3,10,11]

Common non-surgical treatment methods to correct a Class II skeletal malocclusion include the use of headgear or functional appliances; however, fixed functional appliances offer an advantage due to their lack of dependence on patient compliance. The Herbst appliance is a fixed functional appliance that is widely used for

Class II correction and has been extensively researched since its reintroduction by Pancherz in the 1970's.[12] The Herbst was designed to alter the sagittal position of the mandible by continuously posturing it forward with the goal of possibly stimulating condylar growth or redirecting mandibular growth in a favorable direction.[12,13] Additionally, the Herbst is thought by some to act by restricting maxillary anteroposterior growth.[3,13-20] Dentally, a posterior force is placed on the maxillary teeth and an anterior force is placed on the mandibular teeth with the appliance.

Consistent documented treatment effects of the Herbst appliance include proclination and anterior movement of the mandibular incisors, overjet reduction, improvement of the first molar relationship through mesial movement of the mandibular first molars, and a reduction of the ANB angle.[12] Other common, but not universal, findings include retroclination of the maxillary incisors, distalization and intrusion of the maxillary molars, and either no change or a slight increase in the mandibular plane angle.[3,12,13]

A fairly consistent finding throughout the literature is the treatment effect of maxillary growth restriction with the Herbst appliance, which has been described as a "headgear effect."[3,13-20] Several studies have reported that Herbst treatment also causes an overall increase in total mandibular length in addition to the maxillary restrictive "headgear effect."[3,13,15,21] A systematic review by Cozza et al. reported that 66% of samples from 22 studies demonstrated clinically significant supplementary elongation in total mandibular length (>2mm) as a result of functional appliance treatment.[2] Other studies including a systematic review by Barnett et al. have reported minimal maxillary skeletal effects and a lack of a "headgear effect" on the maxilla.[12] The same systematic review by Barnett et al. also concluded that the mandibular skeletal effects of the Herbst are also controversial.[12] Significant and non-significant mandibular skeletal changes were found by the different studies reviewed. Siara-olds et al. reported finding no significant long-term dentoskeletal differences between Herbst treatment groups and matched controls and no significant soft tissue changes.[14] A systematic review of soft tissue changes with fixed functional appliances by Flores-Mir et al. found no significant changes for the chin position measured at soft tissue pogonion.[22] Thus, the skeletal effects of the Herbst are debated, but at the most, the Herbst is thought to restrict maxillary growth and possibly increase total mandibular length.

Early animal studies have demonstrated that posturing the mandible forward can produce an increase in cellular activity at the condylar head as well as an increase in mandibular length, but the effects on humans are more controversial.[2,12,23-28] Some studies have reported condylar and glenoid fossa modeling following the use of various types of functional appliances in humans.[13,14,18] Other studies, particularly those with long-term data, found no significant glenoid fossa changes.[15,29] Although the amount of condylar growth and fossa remodeling changes are disputed, a significant change in condylar growth direction with the Herbst appliance is a substantiated finding that has been supported by many studies.[15,27,30,31] Anterior repositioning of the mandible has been shown to result in a redirection, rather than augmentation, of condylar growth. Greater posteriorly directed condylar growth is observed with the Herbst appliance, and even more pronounced posterior directional changes are seen in hyperdivergent patients treated with the Herbst.[15,30] While the redirection of condylar growth has been shown in some studies to produce a tendency for increased mandibular length, the mandible is not shown to be displaced anteriorly, and an increase in chin projection is not seen.[15] Inferior displacement of the anterior mandible has been shown, however, which supports the notion that mandibular rotation could potentially be playing a role in the Herbst mandibular skeletal effects.[15]

Although the dental changes produced by the Herbst appliance are well documented and consistent in the literature, the skeletal changes produced by the Herbst, including whether or not a maxillary growth restriction, increase in total mandibular length, long-term change in mandibular position and chin position, and glenoid fossa modeling exist as treatment effects, remain a clear source of controversy. Conflicting evidence supporting both the presence and absence of these proposed treatment effects has been reported by different studies. Much of the debate exists in part because of the different methods of analysis employed by the published articles and reviews.[12] Many studies do not distinguish between different mandibular rotation and growth patterns in subjects, maturational status, different Herbst appliance designs or protocols, lack a comparison of treatment effects to an untreated control group, lack long-term data, or do not examine the effects of different functional appliances individually. Thus, there is a considerable ambiguity of the evidence for the skeletal effects of Herbst treatment, and a need for further investigation. Of significant importance to profile improvement in Class II mandibular retrusive individuals is the lack of definitive information on the Herbst's effects on chin position.

Throughout the literature, the proposed mechanisms for improving anteroposterior chin position include condylar growth changes, repositioning of the glenoid fossa, and counterclockwise forward rotation of the mandible.[3] The anterior tip of the chin is stable and undergoes little or no remodeling, therefore, it is established that the chin does not come forward due to remodeling or growth of the chin itself.[32-35] Schudy proposed that the vertical growth of the maxilla and vertical maxillary and mandibular dentoalveolar growth are the primary determinants of chin position.[3] In other words, for an improvement of chin position to occur, the condylar growth must exceed the vertical growth of the corpus of the maxilla and the vertical growth of the maxillary and mandibular processes.[3] Sinclair and Little also supported this belief.[36] This theory, however, has not been supported by subsequent research.[3] LaHaye et al. along with many others support the belief that true mandibular rotation plays the primary role in determining anteroposterior chin position.[3,8,9,32,37] Bjork and Skieller demonstrated that anterior movements of the chin are strongly related to true mandibular rotation. Their findings also suggested that changes in condylar and dentoalveolar development occur to compensate secondarily to mandibular rotation.[37] Mathematical models produced by Buschang and Santos-Pinto have shown that mandibular rotation is the most important determinant of horizontal movements of the chin in untreated children and adolescents.[3] LaHaye at al. reported a correlation between the horizontal movements of pogonion and true rotation of 0.64, and Thompson et al. reported a similar correlation of 0.69.[3] This means that 41-48% of the variation in the horizontal movement of pogonion can be explained by true rotation. Thus, while true rotation explains the majority of horizontal chin position, additional information is required to accurately predict chin movements. The multiple regressions in the study by LaHaye et al. supported previous studies that showed that true rotation along with horizontal and vertical changes in the glenoid fossa and condyle accounted for approximately 90% of the variation in horizontal chin position.[3] In order of association, the anteroposterior position of pogonion in both treated and untreated patients is most closely related to true mandibular rotation, followed by the anteroposterior position of the condyle, followed by the anteroposterior position of the glenoid fossa.[3]

With true mandibular rotation as the primary determinant of chin position, it is important to understand the components of true rotation and the mandible's adaptability to rotation in order to comprehend the resultant effects on the facial profile. True rotation refers to the rotation of the mandibular body relative to the anterior cranial base that "truly" occurs, independent of remodeling.[38]

Apparent rotation is the change in the mandibular plane angle including the remodeling changes of the lower border of the mandible; therefore, it is the change that "appears to occur" but does not actually occur.[38] Due to these remodeling changes of the mandibular border, superimposition on the mandibular border and changes in the mandibular plane angle cannot be relied upon to interpret mandibular growth and treatment effects. Instead, true rotation must be examined to accurately determine these effects. True rotation also determines the direction of condylar growth, which affects the shape and sagittal position of the mandible.[38] It has been established through implant and histological studies that growth in mandibular length occurs primarily at the condyle.[39,40]

Dependent on the orientation and individual's growth pattern, the condyle grows superiorly and slightly posteriorly or even anteriorly.[35,39] A ratio of 10:1 superior to posterior condylar growth has been reported.[35] The terms "forward rotator," or "hypodivergent," and "backward rotator," or "hyperdivergent," have been used to describe the condylar and facial growth pattern that an individual may exhibit.[39] Forward rotators display greater condylar growth that is more anteriorly directed than backward rotators. More posteriorly directed condylar growth is exhibited by less forward or backward rotators.[39] A greater counterclockwise or forward rotation of the mandible will produce a greater forward movement of the chin.[41] In contrast, a clockwise or backward rotation of the mandible will result in an adverse posterior movement of the chin.[38]

Since the Herbst appliance postures the mandible forward, the condyle slides down the articular eminence in an anterior and inferior position. The result is a redirection of condylar growth in a posterior direction.[15,30] With posteriorly directed condylar growth having been shown to be associated with a less forward or backward rotation of the mandible, it is logical to believe that the backward rotation of the mandible with Herbst treatment will mask the effects of any potential increase in mandibular growth and have an adverse effect on chin position compared to an untreated individual. If this is found to be true, the effects of Herbst treatment may be in opposition to treatment objectives to improve a mandibular retrusive profile. The existing literature on Class II growth and mandibular rotation suggests that to correct a skeletal Class II malocclusion with an improvement of facial esthetics, it is necessary to consider a treatment approach that provides the greatest amount of forward mandibular rotation to allow for anterior movement of the chin, while also controlling for backward rotation, which produces inferior and posterior movement of the chin with deleterious effects on the profile. However, these treatment effects have not yet been examined with the Herbst appliance.

In the literature, there are three recurring voids of information in the examination of the treatment effects of the Herbst appliance. First, the majority of studies describing skeletal treatment effects of the Herbst appliance fail to account for the mandibular divergence and rotational pattern of the patients. Because the growth patterns of hypo-, normo-, and hyperdivergent patients differ significantly, the patient's vertical tendency is critical for the interpretation of Herbst treatment effects.[38] An untreated hypodivergent patient will have more superior or slightly anterior condylar growth, greater forward rotation, and an increased AP chin position in comparison to an untreated hyperdivergent patient with backward rotation and more posteriorly directed condylar growth. Thus, the changes in chin position will be different between these patients with varying divergence patterns through growth alone. The additional effects of the Herbst appliance, which produces a posterior redirection of condylar growth, have yet to be compared between the three growth patterns. A question that has yet to be answered is whether or not the Herbst appliance decreases the amount of superior or anterior condylar growth in hypodivergent patients and decreases forward rotation and chin projection compared to an untreated hypodivergent patient. Conversely, it is not known if the Herbst further increases the existing posterior direction of condylar growth in a hyperdivergent patient and exacerbates the backward rotation and decrease in chin projection. No studies to date have integrated true mandibular rotation into the interpretation of the results; therefore, these questions cannot be answered with the existing literature. In one of the few studies that documented the subjects' divergence patterns, LaHaye et al. exclusively examined hyperdivergent patients and found that skeletal Class II correction with Herbst treatment was primarily achieved by maxillary growth restriction alone.[3] They did not find any significant increases in SNB, mandibular length, condylar growth, or sagittal chin position, which are treatment effects that have been reported by other studies in which the divergence patterns of the patient sample were not specified or controlled.[2] These contrasting reports of treatment effects in hyperdivergent patients support the belief that the Herbst treatment effects may be different in hyper- versus hypodivergent patients. The patient's vertical growth pattern must be known to accurately interpret the treatment effects of the Herbst, yet the majority of the literature lacks a clear definition of the patient population in these terms.

Second, there is a considerable lack of information about the general effects on chin position with Herbst treatment using appropriate, stable reference points with a comparison of the results to untreated controls. When chin position has been described in the literature, it has been reported most often in terms of SNB or SN-Pg angular measurements. When using angular measurements to interpret sagittal changes, increases in the vertical dimension will mask the anterorposterior changes. Thus, angular measurements are not as accurate for interpreting horizontal and vertical changes in these patients. Millimeter linear measurements from stable reference points in relation to horizontal and vertical reference lines must be used to appropriately evaluate sagittal changes and also distinguish pure treatment changes separate from growth changes. Some studies have reported a small increase in the SNB angle of 0.2-1.4 degrees with Herbst treatment.[3,13,15,42,43] Because B point changes with the eruption and inclination of the mandibular incisors, and Nasion moves forward with growth, the SNB angle is not a stable reference to infer changes in mandibular or chin position with treatment. Pogonion is a more reliable reference point for interpreting changes in chin position since the anterior portion of the chin is stable and does not undergo remodeling. However, few studies have directly measured the treatment effects of the Herbst on the chin itself using Pg as a reference point. Those who have generally reported no significant change in SN-Pg or an inferior movement of Pg with Herbst treatment.[3,15,22] Alternatively, some studies have described an increase in SN-Pg, but did not clearly compare these treatment results to an untreated control group thereby making it difficult to differentiate whether the SN-Pg increase was a result of Herbst treatment versus normal growth. Since Nasion moves forward with growth, as mentioned before with SNB, the SN-Pg angle will change with growth and therefore is not reliable as a stable reference to interpret treatment changes to the chin produced by the Herbst alone. Other studies that reported increases in SN-Pg and correctly compared the results to an untreated control group failed to describe the vertical growth tendency of the samples to determine whether the larger increases in chin position measured at SN-Pg were related to the vertical growth pattern of the selected patients rather than Herbst treatment alone.[14] As alluded to before, if the treated sample was comprised predominantly of hypodivergent patients with a greater forward rotation growth pattern, a larger sagittal change in chin position would be expected than if the sample contained normo- or hyperdivergent patients. Additionally, if the treatment group contained a majority of one divergence pattern, and the control group contained a majority of the opposite divergent pattern, the treatment results on chin position could again be skewed. Thus, few studies have described the sagittal change of the chin with Herbst treatment appropriately with stable reference points, and no studies have done so in patients with different vertical growth patterns with a matched control group to accurately assess whether any changes in chin position were due to growth, the rotational growth pattern of the patient, or the Herbst treatment itself.

Lastly, another topic lacking clear documentation in the literature is the relation of proposed mandibular treatment effects with the Herbst and true mandibular rotation. Though some articles have shown an increase in mandibular length with Herbst treatment, it cannot be inherently assumed that this directly correlates to an improvement in AP chin position, as some studies have suggested, without taking into account true mandibular rotation. Mandibular rotation is the primary determinant of chin position, yet true rotation and its effect on chin position have not been adequately evaluated in previous studies to support or refute the result of any mandibular skeletal effects found with Herbst treatment. Additionally, some studies that reported greater posteriorly directed condylar growth with functional appliances have implied that the posterior growth results in an improved AP position of the mandible and chin.[44,45] However, they did not provide evidence to support this suggested cause-effect relationship. When true rotation is considered, one would believe that the opposite would be true; that the posterior direction of condylar growth is the consequence of backward rotation of the mandible, which moves the chin inferiorly and posteriorly. Therefore, it is not clear whether the increase in mandibular length and posteriorly redirected condylar growth from Herbst treatment results in any improvement in chin position and facial esthetics in the Class II retrognathic profile. When considering true rotation, it is logical to believe these treatment effects would instead have a deleterious effect on the profile of these patients.

There is a lack of conclusive evidence on the exact effects of the Herbst on chin position, and no existing literature that properly correlates true mandibular rotation with the changes in chin position in patients with different divergence patterns. This study will attempt to clarify the true treatment effects of the Herbst appliance on the Class II profile by examining the relation of chin projection changes and true rotation with the Herbst appliance in hyper-, normo-, and hypodivergent Class II patients. With an understanding of how the mandible adapts to rotational changes with the Herbst and the resultant advantageous or adverse changes in chin position, orthodontists will be able to have a more accurate expectation of Herbst treatment effects and will improve their ability to appropriately select patients for functional appliance treatment. Additionally, a better understanding of mandibular rotational changes will aid orthodontists in choosing treatment options that will meet facial treatment objectives including the improvement of a Class II retrognathic profile through an increase in sagittal chin position.

CHAPTER II

INTRODUCTION

A bilateral Class II malocclusion is a common problem occurring in approximately 14.7% of the U.S population.[1] A consistent finding in Class II malocclusion is mandibular retrusion and subsequent retrusive chin position.[2,3] To correct the facial convexity in Class II individuals, chin position must be addressed in order to obtain a significant improvement in facial esthetics. Although not all of the factors involved in facial esthetics are known, a preference for straighter profiles over retrusive chin positions is apparent and well documented in the literature.[3,10,11]

Common non-surgical treatment methods to correct a Class II skeletal malocclusion include the use of headgear or functional appliances. Fixed functional appliances offer the advantage of not requiring patient compliance. The Herbst appliance is a fixed functional appliance that is widely used for Class II correction and has been extensively researched since its reintroduction by Pancherz in the 1970's.[12] It was designed to alter the sagittal position of the mandible by continuously posturing it forward, with the goal of possibly stimulating condylar growth or redirecting mandibular growth in a favorable direction.[12,13] Additionally, the Herbst is thought by some to restrict anteroposterior maxillary growth.[3,13-17,19,20] Dentally, a posterior force is placed on the maxillary teeth and an anterior force is placed on the mandibular teeth with the appliance.[12] These effects produce proclination and anterior movement of the mandibular incisors and improvement of the first molar relationship through mesial movement of the mandibular first molars. Other common, but not universally documented dental effects include retroclination of the maxillary incisors and distalization and intrusion of the maxillary molars.[12]

There is controversy over the skeletal effects of the Herbst. While most studies have reported maxillary growth restriction with the Herbst appliance, which they describe as a "headgear effect,"[3,13-17,19,20] a systematic review reported minimal maxillary skeletal effects and no significant headgear effect.[12] Increases in mandibular length with Herbst treatment have been reported by several studies.[2,13-15,21] However, non-significant mandibular length change has also been reported.[12]

Although the amount of condylar growth and fossa remodeling changes are disputed,[13-15,27,30,31,46-49] a significant change in condylar growth direction with the Herbst appliance has been repeatedly demonstrated.[15,27,30,31] Anterior repositioning of the mandible has been shown to result in a redirection, rather than augmentation, of condylar growth.[15,46] More posteriorly directed condylar growth occurs with Herbst treatment, with the most pronounced posterior changes seen in hyperdivergent patients.[3,15,30,48-50]

The skeletal changes produced by the Herbst remain controversial because of the different methods of analysis that have been employed in different studies.[12] The most pervasive problem in the Herbst literature is the lack of adequate control groups.[12] In order to distinguish between actual Herbst treatment effects and normal growth, an untreated control group must be used for comparison. Because the growth patterns of hypo-, normo-, and hyperdivergent patients differ significantly, the patient's divergence pattern is also critical for the interpretation of Herbst treatment effects. The majority of the Herbst literature does not specify the MPA of the patient sample. Of the articles that do specify the MPA, two exclusively studied hyperdivergent patients,[3,15] and the other three did not have an adequate untreated controls for comparison.[30,51,52] Thus, there is considerable ambiguity concerning the skeletal effects of Herbst treatment. Of particular importance to profile improvement in Class II mandibular retrusive individuals is the lack of definitive information on the Herbst's effects on chin position.

The proposed mechanisms for improving anteroposterior chin position include condylar growth changes, repositioning of the glenoid fossa, and counterclockwise forward rotation of the mandible.[3] Of these, true mandibular rotation plays the primary role in determining anteroposterior chin position.[3,8,9,37,38] Chin projection changes with the Herbst appliance have not previously been examined in relation to true mandibular rotation.

True rotation refers to the rotation of the mandibular body relative to the anterior cranial base that "truly" occurs, independent of remodeling.[53] Apparent rotation is the change in the mandibular plane angle including the remodeling changes of the lower border of the mandible; therefore, it is the change that "appears to occur" but does not actually occur.[53] True rotation also determines the direction of condylar growth, which affects the shape and sagittal position of the mandible.[37] Growth in overall mandibular length occurs primarily at the condyle,[37,39] and depending on the individual's growth pattern, the condyle grows superiorly and slightly posteriorly or even anteriorly.[35,39] Forward rotators (hypodivergent) display greater condylar growth that is more anteriorly directed than backward rotators.[37] More posteriorly directed condylar growth is exhibited by individuals with less than average forward rotation and by backward rotators.[37] A greater counterclockwise or forward rotation of the mandible produces greater forward movement of the chin.[37] In contrast, a clockwise or backward rotation of the mandible will result in an adverse posterior movement of the chin.[37]

When chin position has been evaluated, it has been reported most often in terms angular measurements such as SNB or SN-Pg. Angular measurements are less reliable than linear measurements for interpreting sagittal changes, since multiple landmarks influence them, and they can be masked by increases in the vertical dimension. Some studies have reported a small increases in the SNB angle (0.2-1.4 degrees) with Herbst treatment.[13,42,43] Because B point changes with the eruption and inclination of the mandibular incisors, and the mandibular incisors are known to advance with Herbst treatment, SNB may not accurately represent pure skeletal changes. Pogonion is a more reliable skeletal reference point for interpreting changes in chin position. Chin position changes based on Pg have generally shown no significant AP changes or an inferior displacement of pogonion with Herbst treatment.[3,15,22,31,50,54,55] However, with the exception of LaHaye et al. and Croft et al., none of the articles have provided information on the starting or final mandibular divergence of the treated or control subjects.[3,15,22,31,50,54,55] Therefore, it cannot be determined whether changes in chin position were related to the patients' inherent vertical growth patterns or to the Herbst treatment alone.

Though some articles have shown greater posterior condylar growth and an increase in mandibular length with functional appliance treatment, it cannot be inherently assumed that this directly correlates with an improvement in AP chin position, as some have suggested.[44,56] Based on our understanding of true rotation, one would expect that the opposite would be true (i.e. that the posterior direction of condylar growth is the consequence of the backwards rotation of the mandible, which moves the chin inferiorly and posteriorly). Therefore, it is not clear whether increases in mandibular length and posteriorly redirection of condylar growth with Herbst treatment results in any improvements in chin position and facial esthetics. When considering true rotation, it is logical to believe these treatment effects would instead have a deleterious effect on the profile of these patients.

There is a lack of evidence on the effects of Herbst treatment on chin position in hypo- and hyperdivergent patients and a lack of literature correlating true mandibular rotation to changes in chin position in Herbst patients. Therefore, the primary objective of the present study was to examine the relation of chin projection changes and true rotation in hypo- and hyperdivergent patients. An additional objective was to understand how the mandible adapts to rotational changes. The goal was to provide a more accurate and realistic expectation of treatment outcomes and profile changes with the Herbst appliance in Class II patients, so that practitioners can avoid causing adverse effects on the chin position and use the mandible's adaptability to rotation to maintain or improve chin position.

CHAPTER III

MATERIALS AND METHODS

Sample Description

The sample consisted of growing patients previously treated by one private practice orthodontist. To be considered for this study, the treated patients had to meet the following selection criteria: 1. Class II skeletal relationship (defined by ANB greater than average age and sex-specific norms[57]), 2. Class II Division I malocclusion with ≥ Class II half-step molar and canine relationships, 3. Treatment with Herbst and fixed appliances alone (no adjunctive appliances used), 4. Successful treatment outcomes with Class I molar and canine relationships, overbite of 2-3 mm and overjet of 1-2 mm, 5. Complete records with pre- and post-treatment lateral cephalogram radiographs, 6. Approximately equal numbers of boys and girls, 7. Growing, between the ages of 11 and 14 years, 8. Consecutively treated within the past 7 years.

The treated group included 45 patients (23 boys, 22 girls) treated with stainless steel crown Herbst appliances for an average of 14.2 ± 4.3 months, followed by fixed edgewise appliances. The total mean treatment time was 2.5 ± 0.7 years. The mean pre-treatment age (T1) was 12.6 ± 1.1 years, and the mean age of the patients when the Herbst was placed was 12.6 ± 1.0 years. The mean post-treatment age (T2), after the Herbst and fixed edgewise appliances, was 15.1 ± 1.2 years. The average pre-treatment MPA (SN-GoMe) was 33.7 ± 6.0 degrees.

All of the patients were treated using a standard cantilever Herbst appliance with full coverage stainless steel crowns on the maxillary and mandibular first molars, telescopic cantilever arms off of the mandibular first molars, and a 0.040 mm stainless steel lower lingual arch with occlusal rests on the mandibular first premolars.

The untreated control group was comprised of children from a longitudinal growth study at the Human Growth and Research Center at the University of Montreal.[58] They were drawn from three school districts in Montreal representing the socioeconomic strata of the larger population. The control sample consisted of 45 Class II Division I subjects (23 boys, 22 girls) who were matched to the treated sample based on age, sex, and pre-treatment MPA. At the initial T1 observation, the control sample was 12.4 ± 0.8 years of age; they were followed for 2.2 ± 0.5 years. Their pre-treatment MPA was 34.8 ± 2.9 degrees.

This study was approved by the Texas A&M University Baylor College of Dentistry Institutional Review Board (2015-0040-BCD-EXP, Reference number: 022808).

Cephalometric Methods

Seven skeletal and dental landmarks were identified using standard definitions (Table 1). All cephalograms were digitally traced by one investigator using Dolphin Imaging Software. The linear measurements were adjusted to eliminate magnification. Traditional angular measurements were used to quantify the anterorposterior changes in the maxilla and mandible (SNA, SNB, ANB), mandibular plane angle (S-N/Go-Me), and skeletal convexity (NAPg).

Cranial base superimpositions of the pre- and post-treatment lateral cephalograms were performed for each subject using cranial base stable structures.[59] To quantify the horizontal and vertical changes of the chin, rectangular coordinates were used with a horizontal reference line (RL) constructed on the T1 tracing. The RL was registered on Sella and oriented 7 degrees below the SN plane to simulate natural head position (Fig 1). The AP change in Pogonion was measured parallel to RL, and the vertical change was measured perpendicular to RL (Fig 2). Anterior and superior changes were recorded as positive.

True rotation (rotation of the mandible independent of the modeling changes) was evaluated by adding the amount of apparent rotation to the amount of mandibular border remodeling. Apparent rotation was measured as the T1-T2 change in the MPA. Mandibular lower border remodeling was measured based on the angular changes of the mandibular plane (as defined by Gonion and Menton) after mandibular superimposition.[59]

Statistical Methods

Due to group differences in T1-T2 duration, the changes were annualized to represent changes per year rather than changes over the entire treatment. The distributions of all variables were normal based on the skewness and kurtosis statistics. To examine the treatment effects in relation to the subjects' divergence growth patterns, those with a MPA < 34 were grouped as hypodivergent, and those subjects with a MPA ≥ 34 were grouped as hyperdivergent. Independent samples t-tests were used to evaluate group differences.

CHAPTER IV

RESULTS

There were no statistically significant pre-treatment group differences between the Herbst patients and the untreated control subjects in terms of T1 age, gender, MPA, or sagittal jaw positions (Table 2). The SNA and SNB angles indicated relatively normal positions of the maxilla and mandibular retrusion, respectively.

The hypodivergent Herbst patients showed significant improvements in ANB due to a decrease in SNA and an increase in SNB (Table 3). In contrast, the controls showed no significant changes in these three measurements. Group comparisons showed significant differences in both the SNA and ANB angles, with the hypodivergent Herbst patients showing a significantly greater reduction in both angles. Both the hypodivergent Herbst and the hypodivergent controls showed slight, but statistically significant, amounts of forward rotation. Pogonion came forward and down slightly more in the Herbst than control group, but the group difference was not significant. There was a significant group difference in the change of NAPg, with the hypodivergent Herbst patients increasing significantly, and the controls showing no change.

The ANB angle of the hyperdivergent Herbst patients improved significantly due to a decrease in SNA; the control subjects showed no significant change in either measurement (Table 4). The group difference in the ANB changes was statistically significant. True rotation was also significantly different between the groups, with the hyperdivergent controls showing slight forward rotation and hyperdivergent Herbst patients undergoing slight backward rotation. Neither group showed horizontal advancement of the chin. There was greater inferior displacement of the chin in hyperdivergent Herbst patients, but the group difference was not significant. NAPg increased significantly in hyperdivergent Herbst patients, whereas the controls showed no change, resulting in a significant group difference.

Comparison of the hypo- and hyperdivergent Herbst patients showed no statistically significant difference in SNA, SNB, or ANB (Table 5). True rotation was significantly different, with the hypodivergent Herbst patients showing forward rotation, and the hyperdivergent Herbst patients exhibiting backward rotation. The hypodivergent Herbst patients also underwent significant anterior displacement of Pogonion, while the hyperdivergent patients did not. Again, the group difference was statistically significant. The hyperdivergent Herbst patients also showed greater vertical displacement at Pogonion than the hypodivergent patients, but the difference was not statistically significant. There was no group difference in NAPg; both groups exhibited increases. The hypo- and hyperdivergent controls showed no statistically significant group differences (Table 6). The hypodivergent controls showed statistically significant forward rotation and anterior displacement of Pogonion, whereas the hyperdivergent controls did not. Both groups showed similar amounts of vertical displacement of Pogonion.

CHAPTER V

DISCUSSION

The primary effect of the Herbst in terms of maxillomandibular correction was in the maxilla. The Herbst restricted maxillary growth in both hypo- and hyperdivergent patients, indicative of the "headgear effect" (-0.7 to -0.8 deg/year SNA reduction) reported previously.[3,15] The lack of a statistically significant group difference in SNA between hyperdivergent Herbst patients and hyperdivergent controls was most likely due to the smaller effect and lack of power. LaHaye et al. showed that hyperdivergent Herbst patients had a statistically significant restriction of maxillary growth (-0.7 deg/year SNA reduction).[3] The hyperdivergent patients in the present study were more hyperdivergent than the hyperdivergent patients in the study by LaHaye et al., which may explain the difference in SNA reduction.

The amount of SNA reduction in both the hypo- and hyperdivergent Herbst patients in the present study was similar to the SNA reductions described for cervical-pull headgear (-0.58 to -0.8 deg/year) and high-pull headgear (-0.5 to -1.1 deg/year).[60-63] The treatment changes in SNA for both hypo- and hyperdivergent patients in this study were greater than the SNA change previously reported for untreated individuals with normal growth (-0.001 to 0.65 deg/year).[57] This further supports maxillary growth restriction as a treatment effect of the Herbst. Since the Herbst appliance attaches from the maxilla to the mandible with rigid steel arms to the maxillary and mandibular first molars, the same force that displaces the mandible down and forward is reciprocally exerted on the maxilla. Thus, a backward force is placed on the maxillary dentition and maxilla with the Herbst, which may explain the existence of a "headgear effect."

The Herbst has a positive, though limited, effect on SNB in hypodivergent patients. The change observed in the present study is consistent with the 0.2-1.4 degree increase in SNB previously reported with Herbst treatment.[3,15,64] In contrast, hyperdivergent patients did not show significant changes. LaHaye et al., who only evaluated hyperdivergent patients, also did not find any significant increases in SNB among treated Herbst patients.[3] However, as previously indicated, sagittal changes in mandibular position are best evaluated using Pogonion, since the anterior portion of the chin is stable and does not undergo remodeling.

In the present study, Pogonion did not come forward any more with Herbst treatment than it did in untreated Class II individuals. Existing studies comparing Herbst treatment to untreated controls have consistently found either no significant difference in AP changes at Pogonion or inferior displacement of Pogonion with Herbst treatment.[3,15,22,31,54,55] One study reported a downward and backward displacement of Pogonion.[50] Studies that reported increases in chin projection with functional appliance treatment have consistently failed to specify the pre-treatment divergence pattern of the patients.[14,44,56] For example, Baccetti et al. reported that functional jaw orthopedics with a bonded Herbst appliance had a favorable impact on the advancement of the chin,[56] but the MPA or divergence pattern of the patients was not stated. If their treated group was comprised of more hypodivergent patients, and the controls contained more normo- or hyperdivergent individuals, then the treated group would have shown greater increases in chin projection due to the more favorable growth pattern alone. Without knowing the vertical growth tendency of the samples, it cannot be determined whether changes in chin position or group differences were related to the inherent vertical growth pattern of the selected patients or Herbst treatment alone.

There is a reduction in skeletal convexity (NAPg) with Herbst treatment in both hypo- and hyperdivergent patients, but it is not due to greater advancement of the chin. Numerous studies have reported profile improvements and decreases in facial convexity with Herbst treatment.[22,54,55,65,66] Those with adequate control groups and proper reference points have also found that the decrease in convexity was primarily due to maxillary changes, with no significant differences in AP chin position with treatment.[3,15,22,31,54,55] Therefore, the improvement of the profile and reduction of skeletal convexity with Herbst treatment is due to the restriction of anterior maxillary growth rather than mandibular protrusion.

The Herbst appliance has little or no effect on the mandibular plane angle. The present study found no significant difference in the MPA in hypo- or hyperdivergent Herbst patients in comparison to controls. This is consistent with other studies reporting either no change or a slight increase in the MPA with Herbst treatment.[3,13,15] Despite the lack of change in the MPA, there was significant true rotation occurring that was masked by remodeling of the lower mandibular border. Remodeling of the lower border of the mandible in untreated subjects has been reported to approximate 0.51 to 1.1 deg/year, which is consistently greater than the concomitant changes that occur in the MPA.[38] Due to the remodeling changes of the mandibular border, superimposition on the mandibular border and changes in the MPA cannot be relied upon to interpret mandibular growth and treatment effects. Instead, true rotation must be examined to accurately determine these effects.

The true rotational effects of the Herbst are different in hypo- than hyperdivergent patients. During normal growth, hypo-, normo-, and hyperdivergent untreated individuals generally show forward rotation.[6] The difference is that untreated hypodivergent patients have significantly more forward rotation than untreated hyperdivergent patients.[6] Similarly, the untreated hypo- and hyperdivergent control samples in this study exhibited forward rotation that was consistent with previously published estimates ranging from 0.4-1.0 degrees per year.[67,68] In contrast, the hyperdivergent Herbst patients in the present study exhibited significant backward rotation, unlike the hypodivergent Herbst patients and hyperdivergent controls. Therefore, hyperdivergent patients undergo a deleterious backwards rotation with Herbst treatment. The hypodivergent Herbst patients in the present study exhibited forward rotation that was consistent with previously published estimates (0.4-1.0 deg/year of forward rotation),[67,68] and was similar to the forward rotation exhibited by the hypodivergent control sample. This suggests that hypodivergent patients may be able to overcome the backward rotational effects of the Herbst appliance.

The mechanism producing rotational effects may be inherent to the design of the Herbst. True rotation determines the direction of condylar growth, which affects the shape and sagittal position of the mandible.[38] Since the Herbst appliance postures the mandible downward and forward, the condyle slides down the articular eminence in an anterior and inferior position. This redirects condylar growth in a posterior direction.[15,30,46] Posteriorly directed condylar growth has been shown to be associated with a less forward or backward rotation of the mandible.[38] Therefore, the downward and forward posturing of the mandible with the Herbst appliance should be expected to inhibit forward mandibular rotation or cause backward rotation, which in turn results in posterior redirection of condylar growth and vertical displacement of the chin. Additionally, opening of the gonial angle and an increase in LAFH has been shown to occur with Herbst treatment, which are also indicative of the hyperdivergent backward rotational pattern.

The effect of Herbst treatment on true mandibular rotation in hypo- and hyperdivergent patients has not been examined previously. One possible explanation for the rotational differences between divergence patterns may be the orofacial musculature. Weaker and stronger musculatures have been associated with the development of hyperdivergent and hypodivergent growth patterns, respectively.[69,70] Therefore, with respect to rotation, functional appliances may work best in patients with greater horizontal growth potential and less vertical growth tendencies, often associated with more powerful masticatory musculature.[38] Patients with euryprosopic facial form and powerful jaw musculature undergo more forward true rotation, and therefore, may be better able to overcome the negative rotational effects of Herbst treatment. Leptoprosopic patients with weaker musculature, on the other hand, may have less muscular ability to overcome the backward rotational effects of the Herbst.

Airway provides a second possible explanation for the rotational differences between hypo- and hyperdivergent patients. Airway obstruction is associated with the hyperdivergent phenotype: increased lower facial height, increased total facial height, more retrognathic jaws, and altered tongue position.[71-73] Many studies have shown that individuals with obstructed airways often have habitual open mouth breathing postures.[74-77] Therefore, if the patient's hyperdivergence was due to habitual mouth breathing, their open mouth posture may allow for more expression of the backward rotational effect of the Herbst. Both weak musculature and airway compromise have been associated with lower mandibular posture and the resultant development of the hyperdivergent phenotype.[38]

A third possible explanation for the rotational differences may be morphological. Advancing the mandible horizontally in a patient with a flat occlusal plane (OP) may produce less backwards rotation than advancing down along a steeper OP. Since hyperdivergent patients often have steeper OP's than hypodivergent patients, the greater OP angulation may explain the more backwards rotation that hyperdivergent patients experience.

An increase in overall mandibular length with Herbst treatment has been cited by many studies.[21,56,78-81] However, this does not necessarily contribute to the sagittal maxillomandibular skeletal correction in Class II Herbst patients. While the more posterior redirection of condylar growth increases overall mandibular length, it often does not displace the mandible anteriorly, and chin projection is not increased more than in controls.[3,15,31] Inferior displacement of the anterior mandible has been shown, however.[15,50] Therefore, it is possible that the increase in mandibular length often associated with Herbst treatment is negated due to rotation with the chin displaced down rather than forward.

Clinically, the results of this study hold several implications that may affect patient selection for Herbst treatment. While hypodivergent patients may be able to overcome the negative rotational effects of the Herbst, it does not advance the chin position any more than if the patient had remained untreated. Hypodivergent Class II patients benefit primarily from the Herbst's "headgear effect." The amount of maxillary growth restriction obtained with the Herbst appears to be within the range achieved with headgear, and may provide a non-compliant alternative for these patients.

Hyperdivergent patients also experience a "headgear effect," but it is not as substantial as in hypodivergent patients. This benefits of this effect is limited in hyperdivergent patients because they undergo deleterious backward rotation and increases in LAFH, which worsen facial esthetics. Because of this, hyperdivergent patients are poorly suited for Herbst treatment.

CHAPTER VI

CONCLUSIONS

In this study evaluating Herbst treatment effects in hypo- and hyperdivergent patients and the relation of chin position changes to true mandibular rotation, the following conclusions can be drawn:

1. The primary treatment effect of the Herbst appliance in terms of maxillomandibular correction is in the maxilla. The Herbst produces a significant maxillary growth restriction or "headgear effect."
2. The rotational effects of the Herbst are different in hypo- than hyperdivergent patients. Hyperdivergent patients undergo the deleterious backward true mandibular rotation with Herbst treatment, while hypodivergent Herbst patients undergo forward true mandibular rotation, similar to the forward rotation exhibited by hypodivergent controls.
3. The chin does not come forward any more with Herbst treatment than it does in untreated Class II individuals.

REFERENCES

1. Proffit WR, Fields HW, Jr., Moray LJ. Prevalence of malocclusion and orthodontic treatment need in the United States: estimates from the NHANES III survey. Int J Adult Orthodon Orthognath Surg 1998;13:97-106.

2. Cozza P, Baccetti T, Franchi L, De Toffol L, McNamara JA, Jr. Mandibular changes produced by functional appliances in Class II malocclusion: a systematic review. Am J Orthod Dentofacial Orthop 2006;129:599 e591-512; discussion e591-596.

3. LaHaye MB, Buschang PH, Alexander RG, Boley JC. Orthodontic treatment changes of chin position in Class II Division 1 patients. Am J Orthod Dentofacial Orthop 2006;130:732-741.

4. Baccetti T, Franchi L, McNamara JA, Jr., Tollaro I. Early dentofacial features of Class II malocclusion: a longitudinal study from the deciduous through the mixed dentition. Am J Orthod Dentofacial Orthop 1997;111:502-509.

5. Bishara SE, Jakobsen JR, Vorhies B, Bayati P. Changes in dentofacial structures in untreated Class II division 1 and normal subjects: a longitudinal study. Angle Orthod 1997;67:55-66.

6. Chung CH, Wong WW. Craniofacial growth in untreated skeletal Class II subjects: a longitudinal study. Am J Orthod Dentofacial Orthop 2002;122:619-626.

7. Jacob HB, Buschang PH. Mandibular growth comparisons of Class I and Class II division 1 skeletofacial patterns. Angle Orthod 2014;84:755-761.

8. Buschang PH, Tanguay R, Demirjian A, LaPalme L, Turkewicz J. Mathematical models of longitudinal mandibular growth for children with normal and untreated Class II, division 1 malocclusion. Eur J Orthod 1988;10:227-234.

9. Buschang PH, Tanguay R, Turkewicz J, Demirjian A, La Palme L. A polynomial approach to craniofacial growth: description and comparison of adolescent males with normal occlusion and those with untreated Class II malocclusion. Am J Orthod Dentofacial Orthop 1986;90:437-442.

10. Czarnecki ST, Nanda RS, Currier GF. Perceptions of a balanced facial profile. Am J Orthod Dentofacial Orthop 1993;104:180-187.

11. Spyropoulos MN, Halazonetis DJ. Significance of the soft tissue profile on facial esthetics. Am J Orthod Dentofacial Orthop 2001;119:464-471.

12. Barnett GA, Higgins DW, Major PW, Flores-Mir C. Immediate skeletal and dentoalveolar effects of the crown- or banded type Herbst appliance on Class II division 1 malocclusion. Angle Orthod 2008;78:361-369.

13. Pancherz H. The effects, limitations, and long-term dentofacial adaptations to treatment with the Herbst appliance. Semin Orthod 1997;3:232-243.

14. Siara-Olds NJ, Pangrazio-Kulbersh V, Berger J, Bayirli B. Long-term dentoskeletal changes with the Bionator, Herbst, Twin Block, and MARA functional appliances. Angle Orthod 2010;80:18-29.

15. Croft RS, Buschang PH, English JD, Meyer R. A cephalometric and tomographic evaluation of Herbst treatment in the mixed dentition. Am J Orthod Dentofacial Orthop 1999;116:435-443.

16. LeCornu M, Cevidanes LH, Zhu H, Wu CD, Larson B, Nguyen T. Three-dimensional treatment outcomes in Class II patients treated with the Herbst appliance: a pilot study. Am J Orthod Dentofacial Orthop 2013;144:818-830.

17. VanLaecken R, Martin CA, Dischinger T, Razmus T, Ngan P. Treatment effects of the edgewise Herbst appliance: a cephalometric and tomographic investigation. Am J Orthod Dentofacial Orthop 2006;130:582-593.

18. Manfredi C, Cimino R, Trani A, Pancherz H. Skeletal changes of Herbst appliance therapy investigated with more conventional cephalometrics and European norms. Angle Orthod 2001;71:170-176.

19. Valant JR, Sinclair PM. Treatment effects of the Herbst appliance. Am J Orthod Dentofacial Orthop 1989;95:138-147.

20. Wigal TG, Dischinger T, Martin C, Razmus T, Gunel E, Ngan P. Stability of Class II treatment with an edgewise crowned Herbst appliance in the early mixed dentition: Skeletal and dental changes. Am J Orthod Dentofacial Orthop 2011;140:210-223.

21. Franchi L, Baccetti T, McNamara JA, Jr. Treatment and posttreatment effects of acrylic splint Herbst appliance therapy. Am J Orthod Dentofacial Orthop 1999;115:429-438.

22. Flores-Mir C, Major MP, Major PW. Soft tissue changes with fixed functional appliances in Class II division 1. Angle Orthod 2006;76:712-720.

23. Baume LJ, Derichsweiler H. Response of condylar growth cartilage to induced stresses. Science 1961;134:53-54.

24. Charlier JP, Petrovic A, Herrmann-Stutzmann J. Effects of mandibular hyperpropulsion on the prechondroblastic zone of young rat condyle. Am J Orthod 1969;55:71-74.

25. Elgoyhen JC, Moyers RE, McNamara JA, Jr., Riolo ML. Craniofacial adaptation of protrusive function in young rhesus monkeys. Am J Orthod 1972;62:469-480.

26. McNamara JA. [Neuromuscular and skeletal adaptations to altered orofacial function]. Inf Orthod Kieferorthop 1973;5:346-385.

27. McNamara JA, Jr., Carlson DS. Quantitative analysis of temporomandibular joint adaptations to protrusive function. Am J Orthod 1979;76:593-611.

28. Xiong H, Hagg U, Tang GH, Rabie AB, Robinson W. The effect of continuous bite-jumping in adult rats: a morphological study. Angle Orthod 2004;74:86-92.

29. Popowich K, Nebbe B, Major PW. Effect of Herbst treatment on temporomandibular joint morphology: a systematic literature review. Am J Orthod Dentofacial Orthop 2003;123:388-394.

30. Pancherz H, Michailidou C. Temporomandibular joint growth changes in hyperdivergent and hypodivergent Herbst subjects. A long-term roentgenographic cephalometric study. Am J Orthod Dentofacial Orthop 2004;126:153-161; quiz 254-155.

31. Serbesis-Tsarudis C, Pancherz H. "Effective" TMJ and chin position changes in Class II treatment. Angle Orthod 2008;78:813-818.

32. Buschang PH, Jacob H, Carrillo R. The Morphological Characteristics, Growth, and Etiology of the Hyperdivergent Phenotype. Seminars in Orthodontics 2013;19:212-226.

33. Buschang PH, Santos-Pinto A. Condylar growth and glenoid fossa displacement during childhood and adolescence. Am J Orthod Dentofacial Orthop 1998;113:437-442.

34. Bjork A. Prediction of mandibular growth rotation. Am J Orthod 1969;55:585-599.

35. Baumrind S, Ben-Bassat Y, Korn EL, Bravo LA, Curry S. Mandibular remodeling measured on cephalograms. 1. Osseous changes relative to superimposition on metallic implants. Am J Orthod Dentofacial Orthop 1992;102:134-142.

36. Sinclair PM, Little RM. Dentofacial maturation of untreated normals. Am J Orthod 1985;88:146-156.

37. Bjork A, Skieller V. Facial development and tooth eruption. An implant study at the age of puberty. Am J Orthod 1972;62:339-383.

38. Buschang PH, Jacob HB. Mandibular rotation revisited: What makes it so important? Seminars in Orthodontics 2014;20:299-315.

39. Buschang PH, Gandini Junior LG. Mandibular skeletal growth and modelling between 10 and 15 years of age. Eur J Orthod 2002;24:69-79.

40. Bjork A. Variations in the growth pattern of the human mandible: longitudinal radiographic study by the implant method. J Dent Res 1963;42(1)Pt 2:400-411.

41. Ueno H, Behrents RG, Oliver DR, Buschang PH. Mandibular rotation during the transitional dentition. Angle Orthod 2013;83:29-35.

42. Burkhardt DR, McNamara JA, Jr., Baccetti T. Maxillary molar distalization or mandibular enhancement: a cephalometric comparison of comprehensive orthodontic treatment including the pendulum and the Herbst appliances. Am J Orthod Dentofacial Orthop 2003;123:108-116.

43. Schiavoni R, Grenga V, Macri V. Treatment of Class II high angle malocclusions with the Herbst appliance: a cephalometric investigation. Am J Orthod Dentofacial Orthop 1992;102:393-409.

44. Baccetti T, Franchi L, Toth LR, McNamara JA, Jr. Treatment timing for Twin-block therapy. Am J Orthod Dentofacial Orthop 2000;118:159-170.

45. Pancherz H, Fischer S. Amount and direction of temporomandibular joint growth changes in Herbst treatment: a cephalometric long-term investigation. Angle Orthod 2003;73:493-501.

46. Araujo AM, Buschang PH, Melo AC. Adaptive condylar growth and mandibular remodelling changes with bionator therapy--an implant study. Eur J Orthod 2004;26:515-522.

47. Ruf S, Pancherz H. Long-term TMJ effects of Herbst treatment: a clinical and MRI study. Am J Orthod Dentofacial Orthop 1998;114:475-483.

48. Ruf S, Baltromejus S, Pancherz H. Effective condylar growth and chin position changes in activator treatment: a cephalometric roentgenographic study. Angle Orthod 2001;71:4-11.

49. Paulsen HU. Morphological changes of the TMJ condyles of 100 patients treated with the Herbst appliance in the period of puberty to adulthood: a long-term radiographic study. Eur J Orthod 1997;19:657-668.

50. Pancherz H, Ruf S, Kohlhas P. "Effective condylar growth" and chin position changes in Herbst treatment: a cephalometric roentgenographic long-term study. Am J Orthod Dentofacial Orthop 1998;114:437-446.

51. Ruf S, Pancherz H. The effect of Herbst appliance treatment on the mandibular plane angle: a cephalometric roentgenographic study. Am J Orthod Dentofacial Orthop 1996;110:225-229.

52. Ruf S, Pancherz H. The mechanism of Class II correction during Herbst therapy in relation to the vertical jaw base relationship: a cephalometric roentgenographic study. Angle Orthod 1997;67:271-276.

53. Solow B, Houston WJ. Mandibular rotations: concepts and terminology. Eur J Orthod 1988;10:177-179.

54. de Almeida MR, Flores-Mir C, Brandao AG, de Almeida RR, de Almeida-Pedrin RR. Soft tissue changes produced by a banded-type Herbst appliance in late mixed dentition patients. World J Orthod 2008;9:121-131.

55. Pancherz H, Anehus-Pancherz M. Facial profile changes during and after Herbst appliance treatment. Eur J Orthod 1994;16:275-286.

56. Baccetti T, Franchi L, Stahl F. Comparison of 2 comprehensive Class II treatment protocols including the bonded Herbst and headgear appliances: a double-blind study of consecutively treated patients at puberty. Am J Orthod Dentofacial Orthop 2009;135:698 e691-610; discussion 698-699.

57. Riolo ML. An Atlas of craniofacial growth: cephalometric standards from the University school growth study, the University of Michigan. Center for Human Growth and Development, University of Michigan; 1974.

58. Demirjian A, Dubuc MB, Jenicek M. [Comparative study of growth in Canadian children of French origin in Montreal]. Can J Public Health 1971;62:111-119.

59. Bjork A, Skieller V. Normal and abnormal growth of the mandible. A synthesis of longitudinal cephalometric implant studies over a period of 25 years. Eur J Orthod 1983;5:1-46.

60. Baumrind S, Korn EL, Isaacson RJ, West EE, Molthen R. Quantitative analysis of the orthodontic and orthopedic effects of maxillary traction. Am J Orthod 1983;84:384-398.

61. Schiavon Gandini MR, Gandini LG, Jr., Da Rosa Martins JC, Del Santo M, Jr. Effects of cervical headgear and edgewise appliances on growing patients. Am J Orthod Dentofacial Orthop 2001;119:531-538; discussion 538-539.

62. Jacob HB, Buschang PH, dos Santos-Pinto A. Class II malocclusion treatment using high-pull headgear with a splint: a systematic review. Dental Press J Orthod 2013;18:21 e21-27.

63. Firouz M, Zernik J, Nanda R. Dental and orthopedic effects of high-pull headgear in treatment of Class II, division 1 malocclusion. Am J Orthod Dentofacial Orthop 1992;102:197-205.

64. Hansen K, Koutsonas TG, Pancherz H. Long-term effects of Herbst treatment on the mandibular incisor segment: a cephalometric and biometric investigation. Am J Orthod Dentofacial Orthop 1997;112:92-103.

65. Ruf S, Pancherz H. Dentoskeletal effects and facial profile changes in young adults treated with the Herbst appliance. Angle Orthod 1999;69:239-246.

66. Ruf S, Pancherz H. Orthognathic surgery and dentofacial orthopedics in adult Class II Division 1 treatment: mandibular sagittal split osteotomy versus Herbst appliance. Am J Orthod Dentofacial Orthop 2004;126:140-152; quiz 254-145.

67. Bjork A. The use of metallic implants in the study of facial growth in children: method and application. Am J Phys Anthropol 1968;29:243-254.

68. Jacob HB, Buschang PH. Vertical craniofacial growth changes in French-Canadians between 10 and 15 years of age. Am J Orthod Dentofacial Orthop 2011;139:797-805.

69. Weijs WA, Hillen B. Relationships between masticatory muscle cross-section and skull shape. J Dent Res 1984;63:1154-1157.

70. Kiliaridis S, Kalebo P. Masseter muscle thickness measured by ultrasonography and its relation to facial morphology. J Dent Res 1991;70:1262-1265.

71. Behlfelt K, Linder-Aronson S, McWilliam J, Neander P, Laage-Hellman J. Dentition in children with enlarged tonsils compared to control children. Eur J Orthod 1989;11:416-429.

72. Behlfelt K, Linder-Aronson S, McWilliam J, Neander P, Laage-Hellman J. Cranio-facial morphology in children with and without enlarged tonsils. Eur J Orthod 1990;12:233-243.

73. Woodside DG, Linder-Aronson S, Lundstrom A, McWilliam J. Mandibular and maxillary growth after changed mode of breathing. Am J Orthod Dentofacial Orthop 1991;100:1-18.

74. Bresolin D, Shapiro PA, Shapiro GG, Chapko MK, Dassel S. Mouth breathing in allergic children: its relationship to dentofacial development. Am J Orthod 1983;83:334-340.

75. Subtelny JD. Oral respiration: facial maldevelopment and corrective dentofacial orthopedics. Angle Orthod 1980;50:147-164.

76. Kerr WJ, McWilliam JS, Linder-Aronson S. Mandibular form and position related to changed mode of breathing--a five-year longitudinal study. Angle Orthod 1989;59:91-96.

77. Miller AJ, Vargervik K, Chierici G. Experimentally induced neuromuscular changes during and after nasal airway obstruction. Am J Orthod 1984;85:385-392.

78. Perinetti G, Primozic J, Furlani G, Franchi L, Contardo L. Treatment effects of fixed functional appliances alone or in combination with multibracket appliances: A systematic review and meta-analysis. Angle Orthod 2015;85:480-492.

79. Baysal A, Uysal T. Dentoskeletal effects of Twin Block and Herbst appliances in patients with Class II division 1 mandibular retrognathy. Eur J Orthod 2014;36:164-172.

80. Pancherz H. The mechanism of Class II correction in Herbst appliance treatment. A cephalometric investigation. Am J Orthod 1982;82:104-113.

81. Franchi L, Pavoni C, Faltin K, Jr., McNamara JA, Jr., Cozza P. Long-term skeletal and dental effects and treatment timing for functional appliances in Class II malocclusion. Angle Orthod 2013;83:334-340.

APPENDIX A

FIGURES

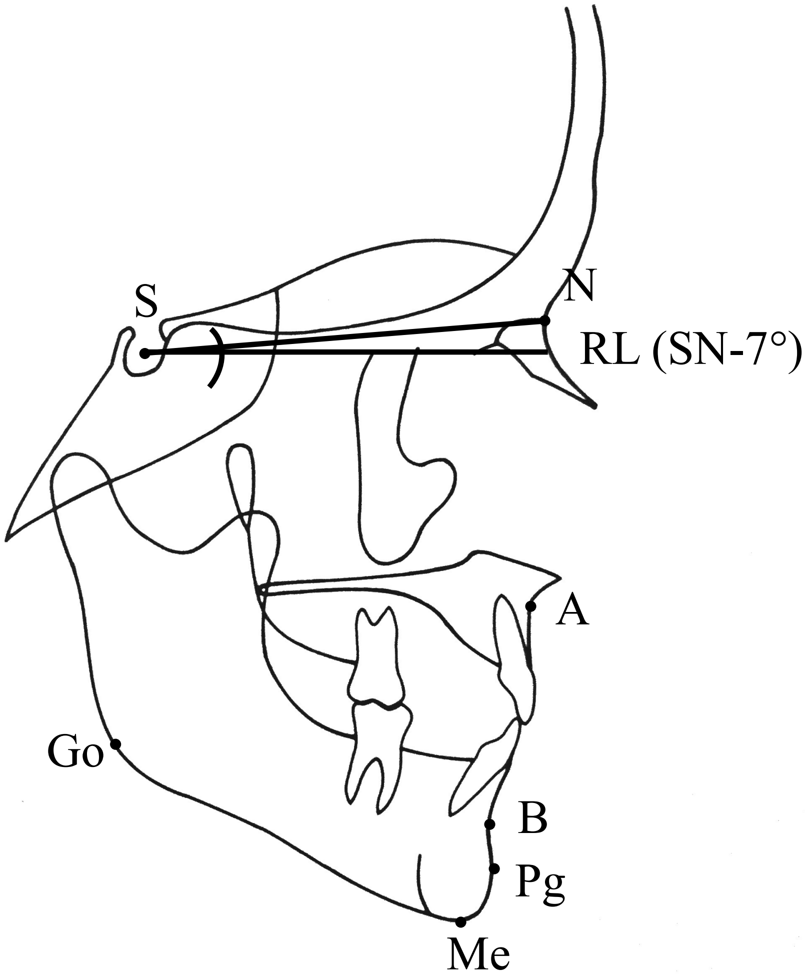

Fig 1a. Cephalometric landmarks and horizontal reference line oriented on the T1 SN-plane minus 7 degrees, registering on T1 sella

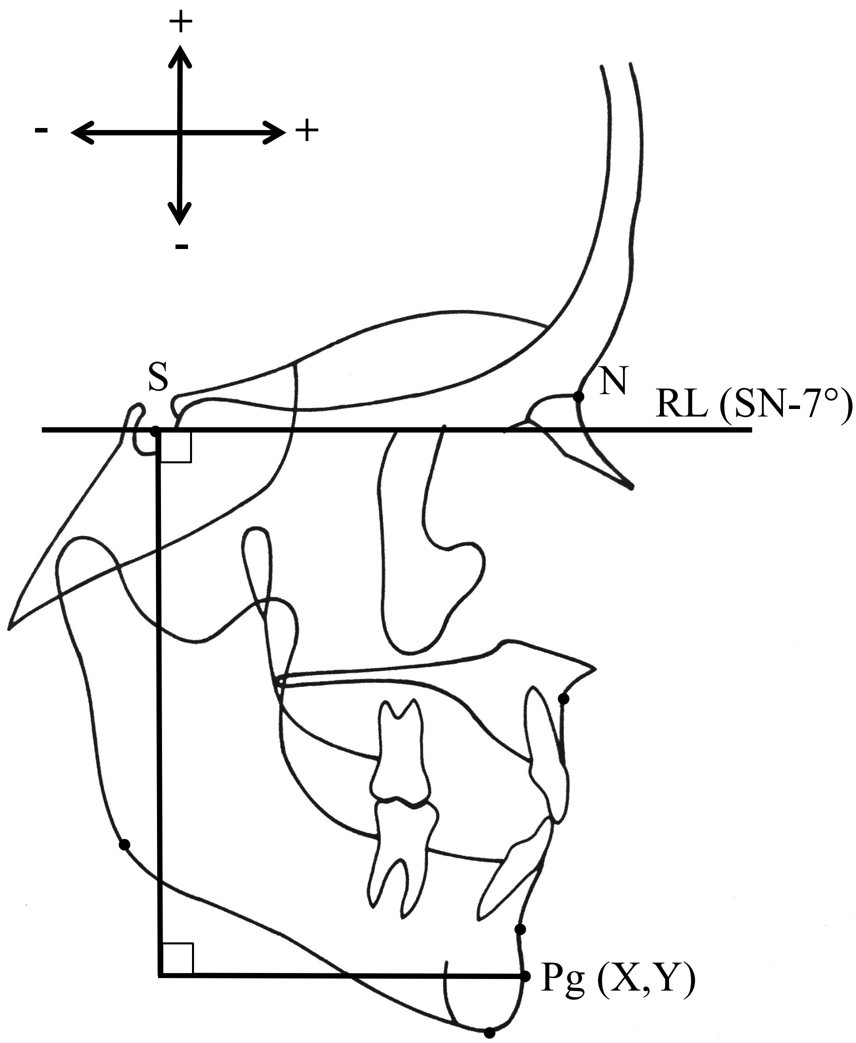

Fig 1b. AP and vertical cephalometric positions measured parallel and perpendicular to the horizontal reference line oriented on T1 SN-7°, registering on T1 sella

APPENDIX B

TABLES

Abbreviation	Definition
S	Sella: the geometric center of the pituitary fossa
N	Nasion: the most anterior point on the frontonasal suture
Pg	Pogonion: the most anterior point on the chin
Me	Menton: the lowest point on the symphyseal shadow of the mandible
Go	Gonion: the point on the curvature of the angle of the mandible located by bisecting the angle formed by lines tangent to the posterior ramus and the inferior border of the mandible
A	A Point (subspinale): the most posterior midline point in the concavity between ANS and prosthion
B	B Point (supramentale): the most posterior midline point in the concavity between infradentale and pogonion

Table 1. Cephalometric landmarks and definitions

T1 (Pre-Treatment)	Herbst (n=45) 23 males, 22 females		Control (n=45) 23 males, 22 females		Group Differences
Measurement	Mean	SD	Mean	SD	P value
Age (years)	12.57	1.08	12.44	0.76	0.530
SN-GoMe (°)	33.70	6.04	34.82	2.89	0.270
SNA (°)	81.5	3.07	80.28	3.00	0.064
SNB (°)	75.81	2.78	76.65	2.39	0.127

Table 2. Pre-treatment group differences between Herbst and control groups

T1-T2 Annualized Changes	Hypodivergent Herbst (n=23)		Hypodivergent Control (n=18)		Group Differences
Measurement	Mean	SD	Mean	SD	P value
SNA (°)	**-0.71**	0.83	0.05	0.65	**0.003**
SNB (°)	**0.45**	0.47	0.18	1.02	0.317
ANB (°)	**-1.16**	0.72	-0.13	0.59	**<0.001**
SN-GoMe (°)	-0.29	0.71	-0.25	0.79	0.870
Rotation (°)	**-0.67**	0.73	**-0.58**	1.23	0.781
Pg Horizontal (mm)	**1.16**	0.96	**0.78**	1.32	0.298
Pg Vertical (mm)	**-2.90**	1.84	**-2.55**	1.06	0.442
NAPg (°)	**2.00**	2.10	0.09	1.02	**0.001**

***Bold** indicates significant changes between T1-T2 (P<0.05)*

Table 3. Comparison of annualized changes (deg/year or mm/year) of hypodivergent Herbst patients and hypodivergent control

T1-T2 Annualized Changes	Hyperdivergent Herbst (n=22)		Hyperdivergent Control (n=27)		Group Differences
Measurement	Mean	SD	Mean	SD	P value
SNA (°)	**-0.59**	0.95	-0.19	0.76	0.110
SNB (°)	0.23	0.67	-0.15	0.83	0.090
ANB (°)	**-0.82**	0.48	-0.04	0.56	**<0.001**
SN-GoMe (°)	-0.06	0.79	0.07	1.19	0.671
Rotation (°)	**0.37**	0.58	**-0.35**	1.12	**0.006**
Pg Horizontal (mm)	0.00	1.30	0.29	1.25	0.427
Pg Vertical (mm)	**-3.32**	1.80	**-2.55**	0.99	0.081
NAPg (°)	**1.82**	0.93	0.28	1.15	**<0.001**

***Bold** indicates significant changes between T1-T2 (P<0.05)*

Table 4. Comparison of annualized changes (deg/year or mm/year) of hyperdivergent Herbst patients and hyperdivergent control

T1-T2 Annualized Changes	Hypodivergent Herbst (n=23)		Hyperdivergent Herbst (n=22)		Group Differences
Measurement	Mean	SD	Mean	SD	P value
SNA (°)	**-0.71**	0.83	**-0.59**	0.95	0.639
SNB (°)	**0.45**	0.47	0.23	0.67	0.202
ANB (°)	**-1.16**	0.72	**-0.82**	0.48	0.072
SN-GoMe (°)	-0.29	0.71	-0.06	0.79	0.306
Rotation (°)	**-0.67**	0.73	**0.37**	0.58	**<0.001**
Pg Horizontal (mm)	**1.16**	0.96	0.00	1.30	**0.001**
Pg Vertical (mm)	**-2.90**	1.84	**-3.32**	1.80	0.443
NAPg (°)	**2.00**	2.10	**1.82**	0.93	0.701

***Bold** indicates significant changes between T1-T2 (P<0.05)*

Table 5. Comparison of annualized changes (deg/year or mm/year) of hypodivergent and hyperdivergent Herbst patients

T1-T2 Annualized Changes	Hypodivergent Control (n=18)		Hyperdivergent Control (n=27)		Group Differences
Measurement	Mean	SD	Mean	SD	P value
SNA (°)	0.05	0.65	-0.19	0.76	0.277
SNB (°)	0.18	1.02	-0.15	0.83	0.231
ANB (°)	-0.13	0.59	-0.04	0.56	0.587
SN-GoMe (°)	-0.25	0.79	0.07	1.19	0.322
Rotation (°)	**-0.58**	1.23	-0.35	1.12	0.532
Pg Horizontal (mm)	**0.78**	1.32	0.29	1.25	0.213
Pg Vertical (mm)	**-2.55**	1.06	**-2.55**	0.99	0.991
NAPg (°)	0.09	1.02	0.28	1.15	0.583

***Bold** indicates significant changes between T1-T2 (P<0.05)*

Table 6. Comparison of annualized changes (deg/year or mm/year) of hypodivergent and hyperdivergent controls